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ABSTRACT

In this paper, we report recent progress on the design of all-fibered ultra-high repetition-rate pulse sources for telecommunication applications around 1550 nm. Based on the nonlinear compression of an initial beat-signal in optical fibers through a multiple four-wave mixing process, we theoretically and experimentally demonstrate that this simple technique allows an efficient and accurate design of versatile pulse sources having repetition rates and pulse durations ranging from 20 GHz up to 2 THz and from 10 ps up to 110 fs, respectively.

Keywords: Nonlinear optics, Optical fiber, Pulse Sources, Pulse Compression, Optical Telecommunication.

1. INTRODUCTION

Generation of high-quality ultra-high repetition rate optical pulse trains around 1.55 μm has become increasingly interesting for many scientific applications such as optical sampling, ultra-high capacity transmission systems, component testing or nonlinear phenomena studies. Unfortunately, the current bandwidth limitations of optoelectronic devices prevent the direct generation of pulses with repetition rate higher than 50 GHz and with a temporal width below a few picoseconds. In order to overcome the limit of electronic bandwidth, an attractive and all-optical nonlinear method was proposed. This technique is based on the gradual transformation of a sinusoidal beating into well-separated pulses through its nonlinear compression in optical fibers. The pulse repetition rate of the source is then simply determined by the frequency of the initial beating. This all-optical approach has been successfully demonstrated with various experimental schemes including dispersion-decreasing fibers [1], adiabatic Raman compression in standard optical fibers [2] and step-like or comb-like dispersion profiled fibers [3]-[5]. However, these techniques often require relatively complicated setups via numerous reshaping stages based on a careful longitudinal dispersion management using custom designed optical fibers [3]-[5]. More recently, this nonlinear compression effect has been observed through a multiple four wave mixing (MFWM) process taking place in a single anomalous dispersive optical fiber and has been proved to be an attractive and efficient alternative method to generate very high repetition rate pulse trains, combining both stability and simplicity of the experimental setup [6]-[9]. This powerful method has been successfully used for the generation of a 1.3-ps high-quality pulse train at 160 GHz and subpicosecond pulses up to 1 THz [9]. Combined with a second stage of compression based on the parabolic reshaping taking place into a normal dispersive optical fiber, we have also demonstrated that pulse sources with lower duty-cycle (up to 1/17) could be obtained at various repetition rates [11]-[12].

In this work, we report several recent and significant progresses on the design of this kind of all-fibered ultra-high repetition-rate pulse sources for telecommunication applications in the C-band. In particular, for the first time of our knowledge, thanks to a phase-lock set-up stabilizing the initial 20-GHz beating frequency, we experimentally managed a direct real-time monitoring of the multiple four-wave mixing compression stage on a 50-GHz optical sampling oscilloscope. We have also demonstrated a record ultra-high repetition pulse source of 2 THz with pulses as short as 110 fs and finally, via a double compression stage configuration, we achieve the generation of 380 fs pulses at 160 GHz.

2. MULTIPLE FOUR-WAVE MIXING COMPRESSION TECHNIQUE

The basic idea of our technique is to convert an initial sinusoidal beating composed of two initial continuous waves (CW) into a well-separated Gaussian pulse train with a duty-cycle of 1/5 through the multiple four-wave mixing process taking place into a standard anomalous fiber [9]. In order to design a pulse source having a repetition rate f, we have derived some very simple rules giving the optimal average power P_0 at the input of the system $P_0 \approx 12.8\ |\beta_2|\ f^{2} / \gamma$ and the optimal fiber length $L \approx 0.071 / |\beta_2|\ f^{2}$, where β_2 and γ are the chromatic dispersion and the nonlinear Kerr coefficient of the fiber, respectively [9]. These design rules then allow the generation of Gaussian chirp-free pulses at the output of the compression fiber with negligible pedestals, a full-width at half maximum (FWHM) of $FWHM \approx 1 / 5 f$ and a peak power evaluated by $P_c \approx 4.57\ P_0$.

3. EXPERIMENTAL RESULTS FROM 20 GHz TO 2 THz

The typical experimental setup is sketched in Fig. 1a. The initial beat-signal is obtained by the superposition of two continuous waves delivered by two external cavity laser diodes (ECL) frequency separated by the repetition rate of the source under test and centered around 1550 nm. A phase modulator, driven around 130 MHz, is used in order to suppress the stimulated Brillouin scattering (SBS) effect occurring in the compression fiber. The resulting beat-signal is then amplified to an average power given by previous relations thanks to an Erbium doped fiber amplifier (EDFA) before injecting into the compression fiber. At the fiber output, the generated pulse train is characterized in both intensity and phase by means of a Frequency-Resolved Optical Gating set-up (FROG) and an optical spectrum analyzer (OSA) [10].

Figures 1b illustrates the experimental results obtained for the 40-GHz pulse source. The compression fiber is a 2.1-km long standard single mode fiber (SMF) and the optimum average power was obtained at 380 mW. The corresponding FROG retrieved intensity and phase are shown in Fig. 1b1. The retrieved intensity profile (solid line) shows well separated reshaped pulses with clearly no pedestal. The phase variation over the compressed pulses is also negligibly small, indicating that pulses are essentially Fourier-transform-limited. Numerical results of pulse propagation based on the generalized nonlinear Schrödinger equation are also plotted in circles. We observe an excellent agreement between the two curves indicating an easy and reliable numerical design of our source. Figure 1b2 shows both experimental and numerical results output spectra. The spectrum exhibits a large number of 40-GHz harmonics due to the MFWM process. Figure 1b3 represents the least squares fit of a Gaussian function to the retrieved pulse shape. As can be clearly seen in this figure, the intensity profile corresponds very well to a Gaussian function with 4.7-ps FWHM which leads to a duty cycle of 1/5. The extinction ratio between peak power and interpulse background is better than 25 dB which stresses the high quality of the pulse source. Finally, the degree of tunability of the 40-GHz pulse source has been evaluated in Fig. 1b4 by monitoring the variation of the FWHM as a function of the central wavelength and shows that more than 20 nm of tunability is achieved around 1555 nm.

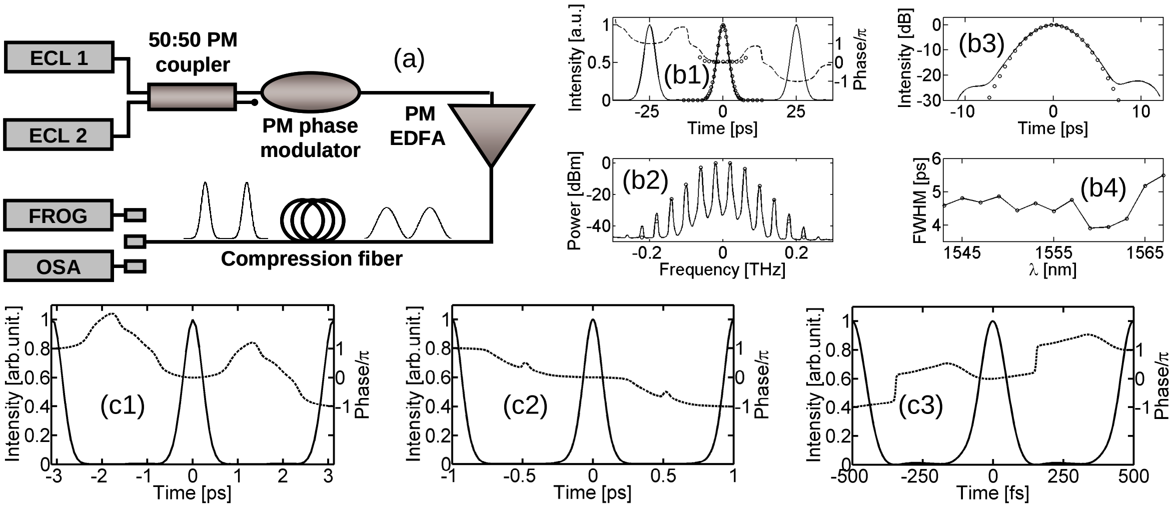

Figure 1 (a) Experimental setup: PM: polarization maintaining (b1) Retrieved intensity (solid line) and phase (dashed line) profiles of the generated 40 GHz pulse train using the FROG setup. Numerical results (b2) Experimental spectrum (solid line) and numerical results (circles). (b3) Intensity profile in log scale (solid line) and corresponding Gaussian fit (circles). (b4) FWHM as a function of central wavelength (c1) FROG results: Intensity and phase profiles of the generated 320-GHz pulse train (c2) FROG results for the 1-THz pulse train (c3) FROG results for the 2-THz pulse train.

Figure 1c represents the experimental FROG results obtained at 320 GHz, 1 and 2 THz using a commercial highly nonlinear dispersion flattened fiber (HNL-DFF), (D = 0.7 ps/nm/km, S = 0.008 ps/nm^2/km, γ = 10 W^{-1}.km^{-1}). The retrieved intensity profiles show very well separated pulses, nearly transform-limited, with a FWHM of 500 fs, 170 fs and 110 fs obtained for an input average power of 150 mW, 1.3 W and 5.3 W into a 720-m, 90-m and 16-m long HNL-DFF, respectively.

4. REAL TIME MONITORING OF A 20-GHZ PULSE SOURCE

An improved source was realized at 20 GHz in order to perform a real time observation of the pulse train emerging from the compressor. To this end, the beat signal between two Er-doped fiber lasers was phase-locked against a reference RF oscillator (see Fig. 2a). The lock loop had a bandwidth of about 1MHz, and the total integrated phase noise, as measured from the error signal, was of $6x10^{-3}$ radian. Fig. 2(b) and 2(c) show the intensity profile and Eye-diagram of the 20 GHz-pulse train generated in the compressor and monitored on a 50-GHz optical sampling oscilloscope. These results are in excellent quantitative agreement with numerical predictions (Fig. 2b, circles).

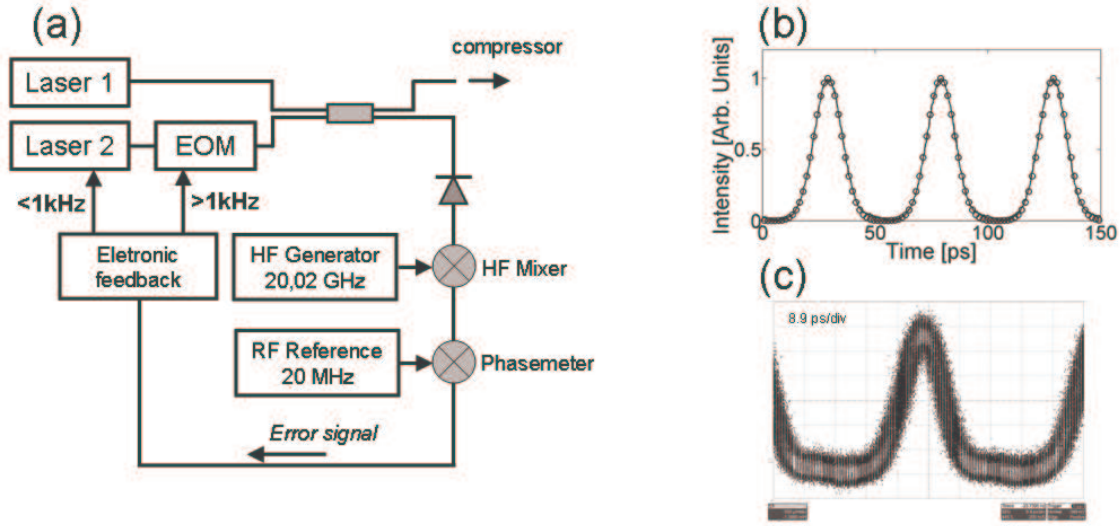

Figure 2 (a) Experimental setup showing the stabilization of the beat signal. EOM: electroptic phase modulator. (b) Intensity profile measured with a 50GHz optical sampling oscilloscope (solid line) compared with numerical simulations (circles). (c) Eye-diagram of the 20 GHz-pulse train.

5. GENERATION OF LOWER DUTY CYCLES

We have seen in the previous parts that a single-stage compression set-up aims to convert an initial sinusoidal beating into a well-separated Gaussian-like pulse train with a duty-cycle of 1/5 through the multiple four-wave mixing process [9]. In this part, we demonstrate the possibility to achieve much lower duty-cycles by reducing the pulse width in a second stage of compression. Basically, the second stage allows the passive reshaping of the Gaussian pulses into a train of linearly chirped Parabolic-like pulses by combining both effects of self-phase modulation and normal dispersion regime in a highly nonlinear fiber [11]. At the output of the second segment, the linear chirp of these pulses can therefore be compensated by simply adding an adequate length of anomalous dispersion fiber or Bragg grating, which constitutes the final stage of the set-up providing nearly transformed-limited recompressed pulses. Figures 3a and 3b show the experimental results obtained at 40 GHz by means of a second stage composed of a 7.7-km long nonzero dispersion-shifted fiber (NZ-DSF, dispersion D=-1.5 ps/nm.km, γ= 1.7 $W^{-1}.km^{-1}$) followed by a 500-m-long HNLF (D = -0.5 ps/nm.km, γ = 13 $W^{-1}.km^{-1}$) in order to increase the linear chirp of the parabolic pulses. Finally a 630-m long SMF fiber ensures a linear pulse recompression. It is important to note that no additional amplifier was used between stage 1 and 2. Figure 3a shows the FROG results and exhibits a nearly side lobe-free temporal intensity profile with a temporal width of 1.8 ps (duty cycle of 1/14). The chirp is quite flat over most of the central part of the pulse. The spectrum of the generated 1.8-ps 40-GHz pulse train is plotted in Fig. 3b and exhibits a symmetric good quality envelope constituted by many generated harmonics separated by 40 GHz as well as an optical signal-to-noise ratio in excess of 35 dB. The generated pulses are then fully suitable for 160-GHz optical time division multiplexing (OTDM) telecommunication applications. Figure 3c and 3d show the experimental results obtained at 160 GHz when a second stage of compression is used. In this case, the second stage is made of a 500-m-long HNLF (D = -0.56 ps/nm.km, γ = 9 $W^{-1}.km^{-1}$) followed by 15 m of SMF. The retrieved intensity profile (Fig. 3c) reveals that the 160-GHz pulses have a Gaussian shape with a FWHM of 380 fs, corresponding to a very low duty cycle of 1/17. The retrieved phase (dashed line) is also pretty flat, confirming that pulses are nearly transform-limited. Finally, the available peak power exceeds 6 W, which is quite high compared to the literature [5]. Finally, the output spectrum (Fig. 3d) is close to a Gaussian envelope (dashed line) having a full-width at half-maximum of 1.1 THz. The time-bandwidth product of 0.45 is fully consistent with the value 0.44 usually associated with Fourier-limited Gaussian pulses.

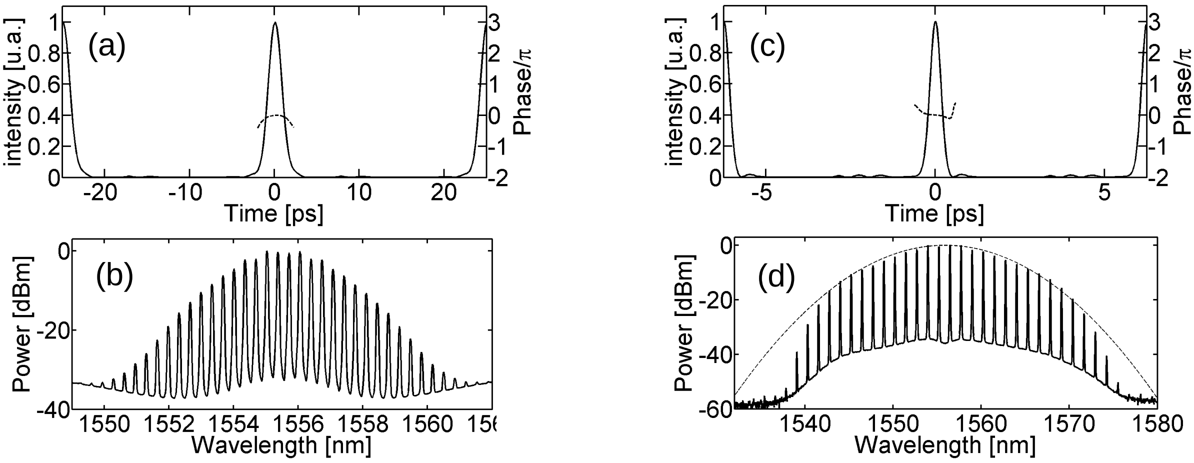

Figure 3 (a) Intensity and phase profiles of the generated 40-GHz pulse train in a double compression stage configuration, FWHM = 1.8 ps (b) Corresponding spectrum (c) and (d) Similar analysis as (a) and (b) obtained for a repetition rate of 160 GHz, FWHM = 380 fs.

6. CONCLUSIONS

In this work, we have reported recent progress on the design of all-fibered ultra-high repetition-rate pulse sources around 1550 nm. Based on the nonlinear compression of an initial beating in optical fibers through a multiple four-wave mixing process, we have experimentally demonstrated that versatile high quality pulse sources having repetition rates and low duty-cycles ranging from 20 GHz to 2 THz and 1/5 to 1/17 could be achieved.

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